# Temperature-Dependent Electroluminescence from CdTe/CdS solar cells

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## ABSTRACT

Electroluminescence (EL) from polycrystalline CdTe/CdS solar cells was studied over the temperature range – 30 C to 25 C.  We are able to observe above-background EL at forward current densities as low as 3 mA/cm$^2$ , allowing us to explore the EL behavior at current-voltage regimes within the normal operating parameters of the device.   The EL spectrum is very similar to the photoluminescence (PL) spectrum, and is independent of applied voltage.  We show that the EL most likely originates from injected electron-hole recombination at the CdTe/CdS junction.  The total EL intensity is found to vary as a power-law function of current, $EL \sim I^b$ , where I is the forward current density and b is a constant.  The value of b varies from sample to sample and decreases with increasing temperature.   EL intensity typically is much more sensitive to device deterioration with light soak stress than is cell efficiency.

## INTRODUCTION

Thin film CdTe/CdS solar cells show great promise for low-cost photovoltaic applications, having already achieved conversion efficiencies of over 16 % (Ref 1).  Much progress has been made in the past decade in achieving a fundamental understanding of CdTe/CdS device operation, but further advances are necessary to make continued progress in conversion efficiency.  In a-Si photovoltaic devices, an important characterization tool has been electroluminescence (EL) (see, for example, the review by Han *et al*[2] and the references therein).  However, in CdTe/CdS devices, few EL studies have been performed.  Potter *et al* first reported the existence of EL at temperatures of approximately 10 K in CdTe/CdS solar cells[3]. We first reported EL measurements in Ref. 4.  Recently, Feldman *et al*[5] presented room-temperature spatially resolved EL data from cells (stressed and unstressed) operating at forward current densities of over 200 mA/cm$^2$ and more recently[6] similar studies with currents as low as 33 mA/cm$^2$. In this work, we report EL at room temperature in CdTe/CdS solar cells operating at forward current densities from 3 mA/cm$^2$ to 20 mA/cm$^2$.  These conditions are comparable to those experienced by a typical device.  Comparison with photoluminescence spectra from the same samples suggests the EL emission originates from the CdTe/CdS junction region.

The total EL intensity is found to vary as a power-law function of current, $EL \sim I^b$ , where I is the forward current density.  The exact value of *b* varies with temperature and from sample to sample.  We also present preliminary results of the effect of stressing on EL.

## EXPERIMENTAL DETAILS

Samples were standard glass/SnO$_2$:F/CdS/CdTe/Cu-Au photovoltaic devices.  CdS (0.12 microns) and CdTe (2.3 microns) were deposited by rf-sputtering.  Back contacts were

approximately 0.15 cm$^2$ circular dots of 4 nm of Cu and 20 nm of Au deposited by thermal evaporation. Photoluminescence (PL) spectra were taken at an excitation power of 4 mW with a Kr laser (752 nm) focused onto the CdTe through the glass and CdS layer. PL emission was collected with a lens into a triple-grating spectrometer with CCD detector. EL spectra were taken from the same spot on the sample immediately following the PL experiment with the same optical system. Integrated EL intensity measurements were made with a different system by placing the sample directly in front of a photomuliplier tube (PMT). Because no dispersing or focusing optics are used, losses due to these components are avoided and lower total EL intensities can be measured. Integrated EL intensity was measured as a function of applied voltage and forward current using a standard PC-based data acquisition card to ramp the applied voltage and measure the resulting current. Temperature was varied by placing the sample on the cold finger of a liquid nitrogen refrigerator.

## RESULTS AND DISCUSSION

### PL and EL Spectra

The PL and EL spectra from a CdS/CdTe solar cell is shown in Figure 1. As mentioned above, the PL is excited using a 1.76 eV Kr laser from the glass side. The glass and CdS layer are virtually transparent to light of that energy, while the $CdS_xTe_{1-x}$ alloy layer at the CdS/CdTe interface has a band gap of approximately 1.48 eV[7,8]. Thus the incident beam is absorbed at the CdS/CdTe junction and the PL originates from this region. The EL was excited by a forward bias voltage of 2V resulting in a current of 100 mA/cm$^2$. The junction PL spectrum has a peak near 1.48 eV, consistent with a band-to-band transition in the junction alloy region. PL from the pure CdTe region has been shown to have an energy of 1.50 eV. The EL spectrum, although less intense than the PL is almost identical in shape and peak position. The EL intensity increases with increasing device voltage and current (see below) but the overall shape and peak position of the emission are constant with device voltage and current.
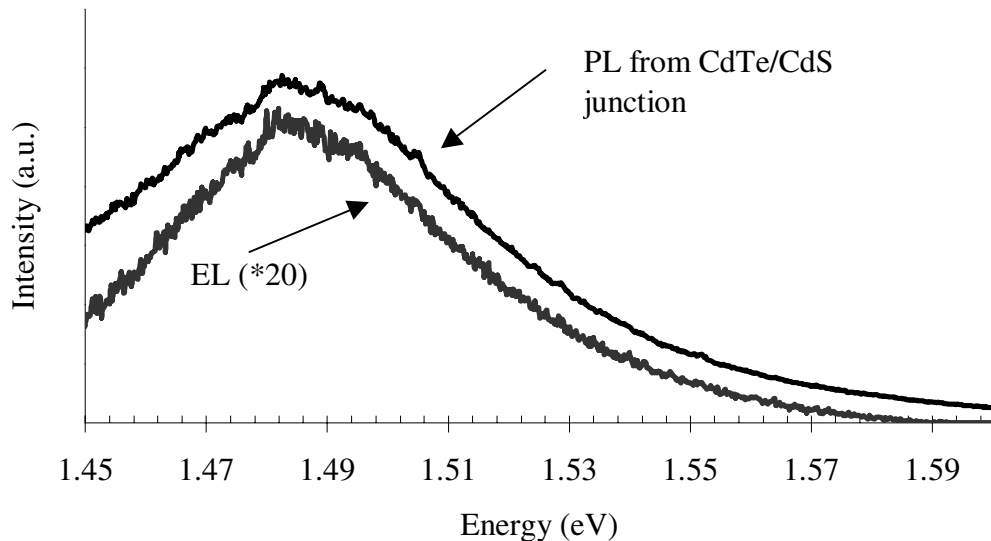


**Figure 1:** 300 K PL and EL spectra from a CdS/CdTe solar cell near the CdS/CdTe interface.

We have thus far not detected any EL at higher emission energies, including those near the CdS band gap. Thus we propose that the EL is originating from the CdTeS alloy layer at the CdS/CdTe interface.

## EL vs. current density

Shown in Figure 2 is the EL intensity vs the device current density for a typical device. We find that for a large number of cells, fabricated under a variety of conditions, the EL intensity exhibits a power law dependence on the device current density. We fit the EL vs I data to the equation

$$EL = aI^b , \tag{1}$$

Where EL is the integrated emission intensity, I is the current density, and $a$ and $b$ are constants. The values of the parameters $a$ and $b$ vary from sample to sample.

The relationship expressed in equation (1) can be understood qualitatively through the following simple analysis: In order for EL to occur, an electron and hole must be in the same region of space in the device (their wave functions must have significant overlap). The closer the two particles are to one another, the more likely they are to recombine. When the solar cell is operated in forward bias, an electron-hole pair may be formed when an electron injected from the n-type CdS encounters a hole injected from the p-type CdTe. Note that the total current $I = I_n + I_p$ where $I_n$ is the electron current and $I_p$ is the hole current. However, the probability of an electron and hole being in the same region of space (close enough to recombine) is proportional to the product of the electron density, $n$, and the hole density, $p$, thus the EL intensity, EL, is proportional $n*p$ . In order to illustrate how the EL intensity is expected to depend on current density, consider two extreme cases:
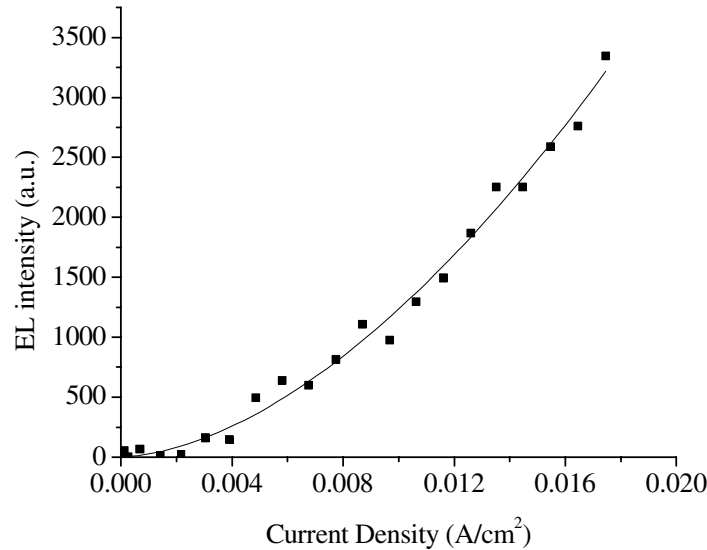


**Figure 2:** EL vs. I data (squares) for a typical device at room temperature (T = 24 C) with theoretical fit (solid line) to equation (1) with a = 3.4 x $10^6$ and b = $1.72 \pm 0.06$

(1) Consider the case in which the electron current and the hole densities are approximately equal over a wide range of applied device voltage. If the voltage applied to the device is increased so that both the electron density and hole density increase by a factor of 2, the total current will increase by a factor of 2, but the EL intensity will increase by a factor of 4, i.e.

$$EL \sim I^2 \text{ (case 1)}$$

(2) Consider the case in which only the injected electron current is significant, and the injected hole concentration, $p$, is small compared with the doped level. Then, total current I is approximately equal to $I_n \sim n$, while EL is proportional to the product $n*p$, with $p$ being approximately constant. Therefore, an increase in current by a factor of 2 will increase EL by a factor of 2, i.e.

$$EL \sim I \text{ (case 2)}$$

In the simple case when the ratio of electron density to hole density is constant with changing applied voltage, the actual device behavior may vary between these two extremes, so that we expect in general, $EL \sim I^b$, $1 < b < 2$ (general case with constant $I_n/I_p$ )

We have also measured the EL vs. I relationship as a function of temperature from –30 C to 24 C for a number of devices. EL vs. I is shown for a typical device (the same device as in Figure 2) is shown in Figure 3. As the temperature is varied, we note that the relationship is still well-described by equation (1), but the exponent $b$ decreases with increasing temperature, as shown in Figure 4. We have seen qualitatively similar behavior in a large number of cells. Note that below about – 20 C, the exponent parameter $b$ is above 2 for the device shown. In fact, in some devices we have observed b > 2.5. That indicates that the simple analysis above, that predicts $1 \geq b \geq 2$, is overly simplistic. One possible extension of the model involves allowing $I_n/I_p$ to be a function of device voltage. Additional efforts are underway to understand the implications of $b > 2$ and the possible effects of trapped charge, potential fluctuations, and non-radiative recombination processes
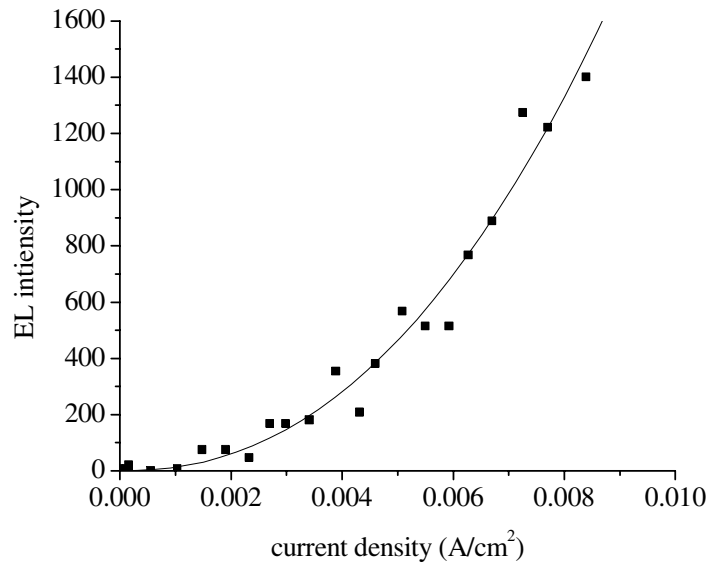


**Figure 3:** EL intensity vs. current density at –30 C for a typical device. Fitting parameters for equation 1 are $a = 6.8 * 10^7$ and $b = 2.25 \pm 0.14$

## Effects of Light Soaking

Experiments on several samples stressed at one sun intensity at $V_{OC}$, ~60 C, shows that after two weeks of light exposure, overall EL intensity decreased by one to two orders of magnitude, while photovoltaic efficiency decreased only by 5 to 20 percent in the particular cells studied. Thus it appears that EL can be very
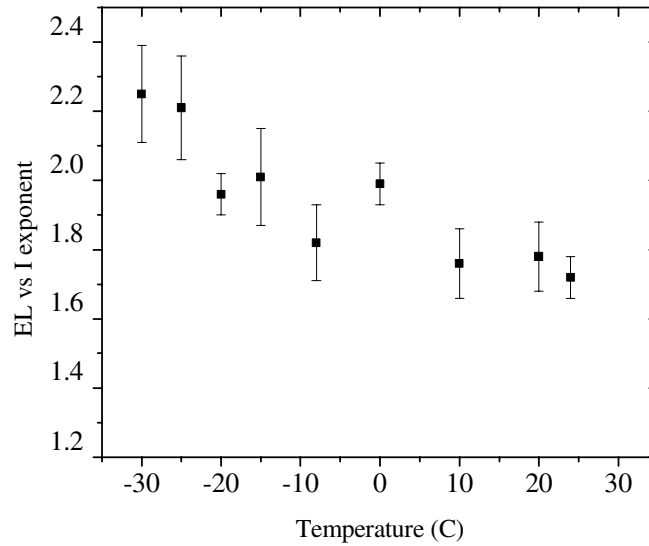


**Figure 4:** EL vs I exponent *b* vs Temperature

sensitive to changes that occur in the device during light exposure. Cell nonuniformities, such as observed by Feldman, et al, in micro-EL[5,6], and by Shvydka, et al[9,10] in small spot photoluminescence are likely to play a strong role at high forward current densities and may also affect the total averaged EL at low current densities, especially in stressed devices. Additional experiments are underway to more fully understand EL in light-soaked devices.

## CONCLUSIONS

We have observed room temperature EL in CdTe solar cells under bias conditions similar to those encountered during typical device operation. The EL spectrum is similar to the PL spectrum near the device junction. EL intensity exhibits a power-law dependence on device current density, with the exponent varying from sample to sample and with temperature. In several samples, the exponent is over 2, which cannot be explained using the most simplistic model. EL intensity decreases dramatically after light-exposure. EL appears to be a promising tool for understanding CdTe solar cell behavior.

## ACKNOWLEDGEMENTS

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